Molecular gas in young debris disks

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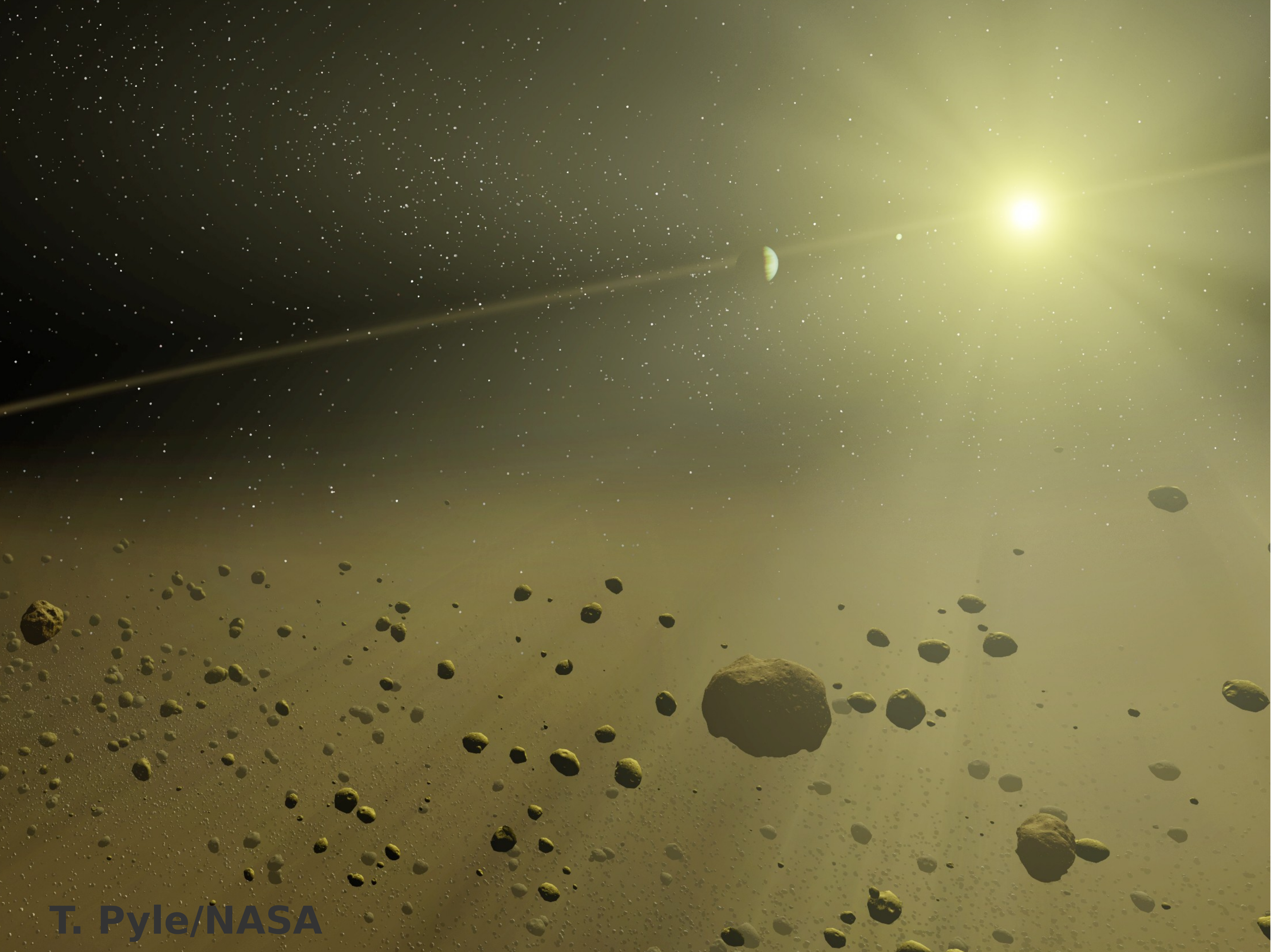
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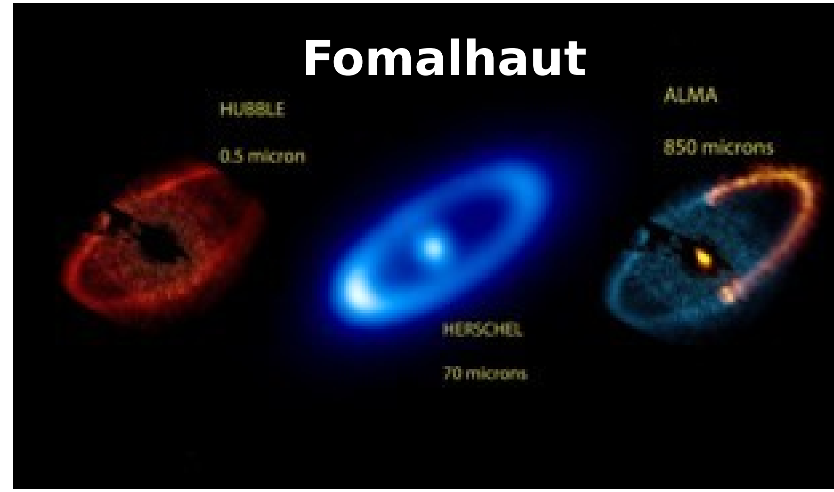
Kalas et al.

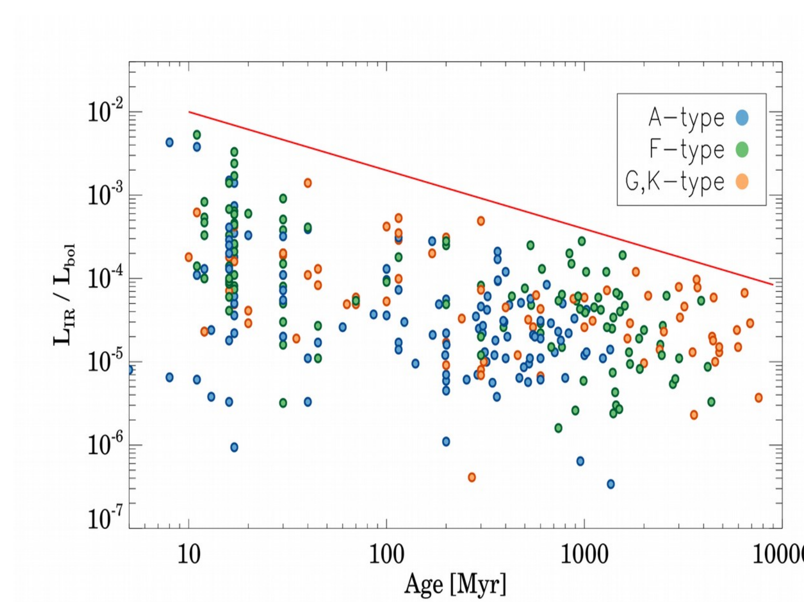
Evolution of circumstellar disks

	Protoplanetary disks	Debris disks
DUST	• primordial • >1 M_{Earth} • $L_{IR} / L_{bol} > 0.01$ • optically thick	• secondary • < 1 M_{Earth} • $L_{IR} / L_{bol} < 0.01$ • optically thin
GAS	• primordial • gas / dust mass ratio ~ 100	• secondary(?) • gas poor(?)
DUST DYNAMICS	• governed by gas	• affected by radiation forces
DISK GEOMETRY	• broad disk	• radially more confined
AGE	• < 10 Myr	• 10 Myr – 10 Gyr

Debris disks: dust content and evolution

- Circumstellar debris dust can be observed in scattered light in the optical/near-IR and in thermal emission at mid- and far-IR wavelengths.
- Several hundreds of debris disks are known. Most of them radiate in the FIR, indicating cold dust, similar to Kuiper-belt.
- Recent FIR surveys measured an incidence of >20% for A-K type main-sequence stars. (B. Matthews's talk)
- From spatially unresolved SED: T_{dust}, fractional luminosity (L_{IR}/L_{bol}, ~amount of dust)
- Many of them are resolved by now : dust morphology, grain properties, grain size distribution.
- Long term evolution: decay of IR excess, can be explained by steady collisional evolution.

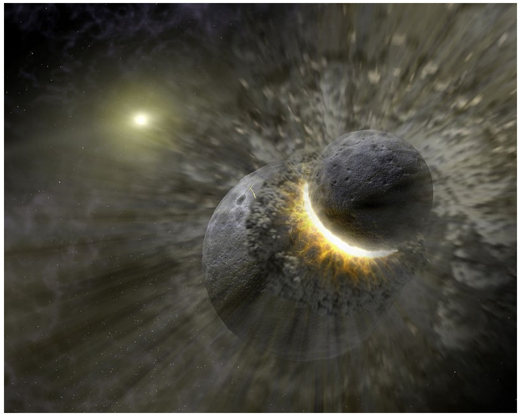




Based on Chen et al. (2014)

Debris disks: gas content?

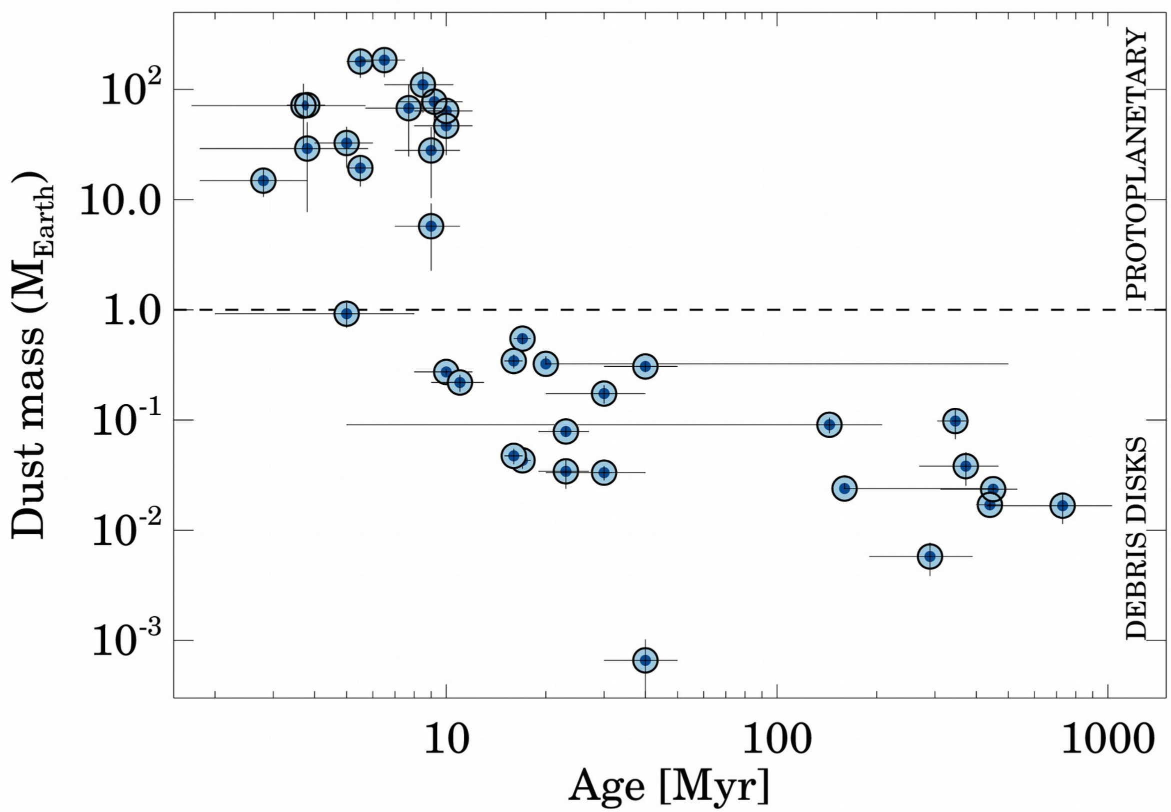
- Theoretical expectation: debris disks may not be completely gas-free
  - in young debris systems leftover gas can be present (primordial origin);
  - general dust producing mechanisms like collisions and sublimation of icy planetesimals and grains may also be accompanied with gas liberation, photodesorption can also lead to gas release.



- **We know very little about the gas content of debris disks!**

Debris disks: gas content, evolution of gas?

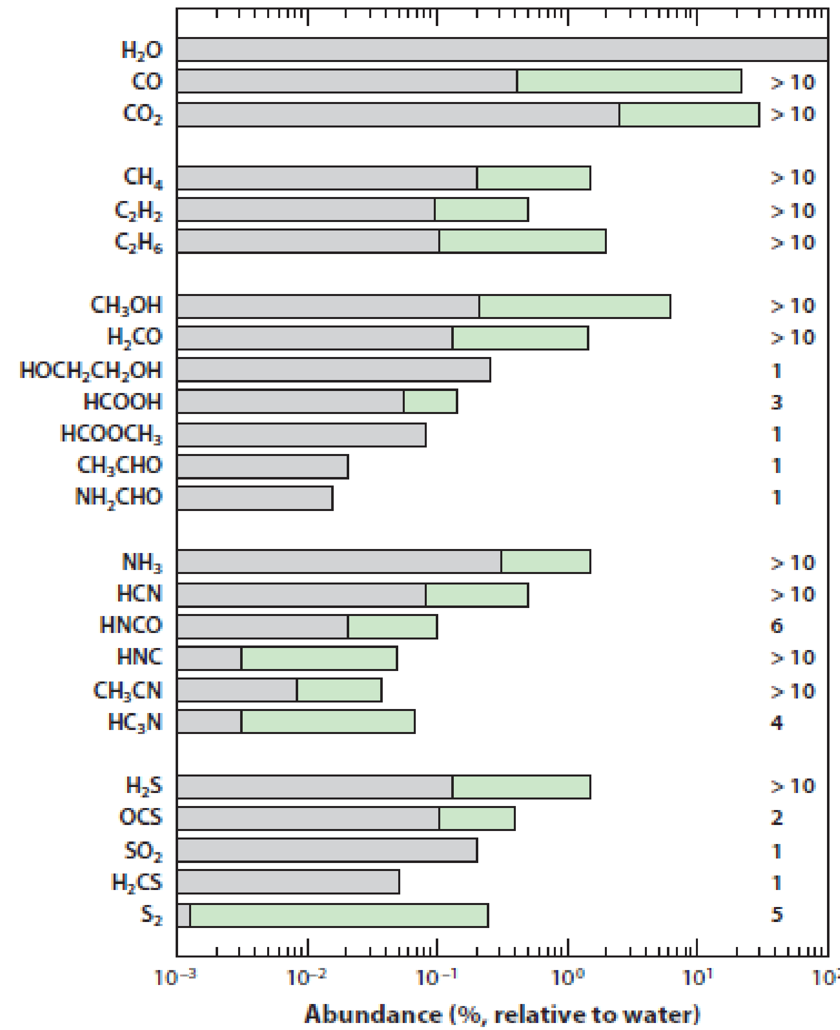
- How much gas is present? What role does it play?
- Transition between protoplanetary disks and debris disks: removal of dust and gas is parallel?
- Long term evolution of secondary gas?



Observation of gas in debris disks

- Gas is more challenging to observe.
- What kind of gas species we expect in debris disks?
  - Leftover primordial gas: protoplanetary composition? Despite its abundance H_2 difficult to detect, but CO as the second most abundant molecule could be a good tracer of cold molecular gas.
  - Secondary gas: icy bodies of our Solar Systems can be used as analogues in terms of composition. CO and its photodissociation products (C, C^+, O) can be used as tracers.
- How can we detect/measure these possible constituents?

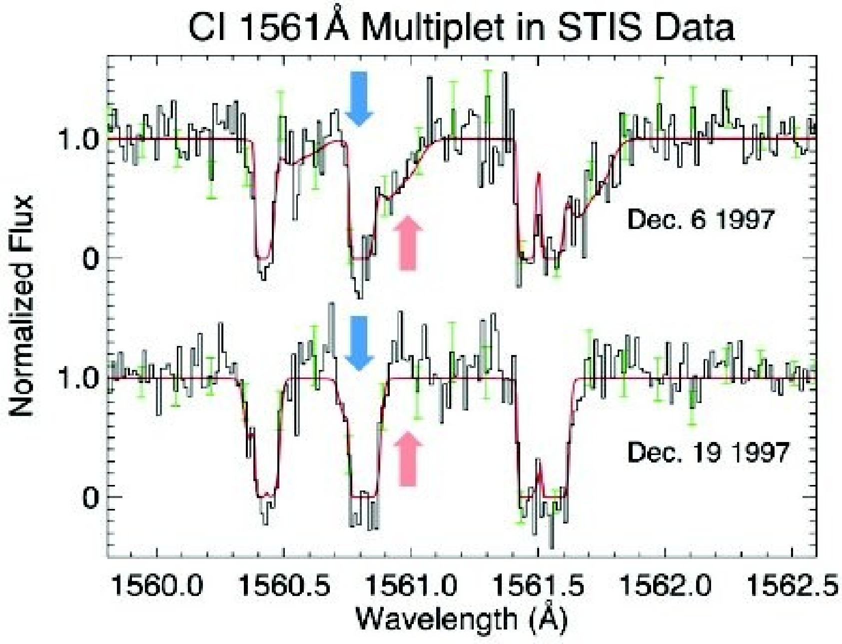
Volatiles in Solar Systems's comets



Mumma & Charnley 2011, ARA&A)

Gas detection via absorption lines

- In special (nearly) edge-on orientation very low amount of gas can be observed via detection of optical, UV absorption lines of different species.
- History: the gas around β Pic was reported by Slettebak in 1975, prior to dust discovery. In the spectra of β Pic there are two types of absorption lines (e.g. Roberge et al. 2000):
  - Stable, narrow component, at the radial velocity of the star – linked to the stable gas disk;
  - Broad, variable, mostly redshifted lines (falling evaporating bodies, FEBs).

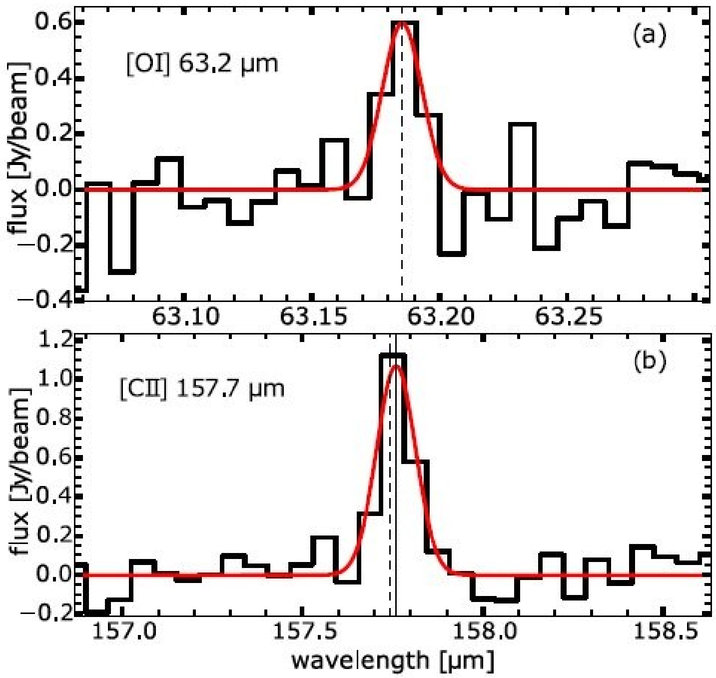


HST STIS spectrum of β Pic (Roberge et al. 2000)

- Similar absorption lines are seen in several A-type stars (Kiefer et al. 2014, Welsh & Montgomery 2015, see also poster of D. Iglesias). Many cases only variable lines: probably exocometary activity, not necessarily linked to a permanent gas disk.

Detection of atomic gas in emission

- Detection of emission lines: independent of disk orientation.
- Herschel Space Observatory: ~40, mostly young (<100Myr) debris disks searched for FIR OI (63 μm), CII (158 μm) emission (mainly in the GASP progamme, PI: W. Dent). Five detections, all of them at A-type stars.
  - Gaseous debris disks known prior to the mission: in β Pic both OI and CII are observed (Brandeker et al. 2016), 49 Cet and HD 32297 are detected in CII (Roberge et al. 2013, Donaldson et al. 2013).
  - New discoveries: HD 172555 (OI, Riviere-Marichalar et al. 2012), HD 181296 (η Tel, CII, Riviere-Marichalar et al. 2014).
- Future opportunity: observation of CI gas at 492 GHz (Band 8) with ALMA.



OI/CII emission lines observed from β Pic with Herschel/PACS (Brandeker et al. 2016)

Can we detect CO in debris disks?

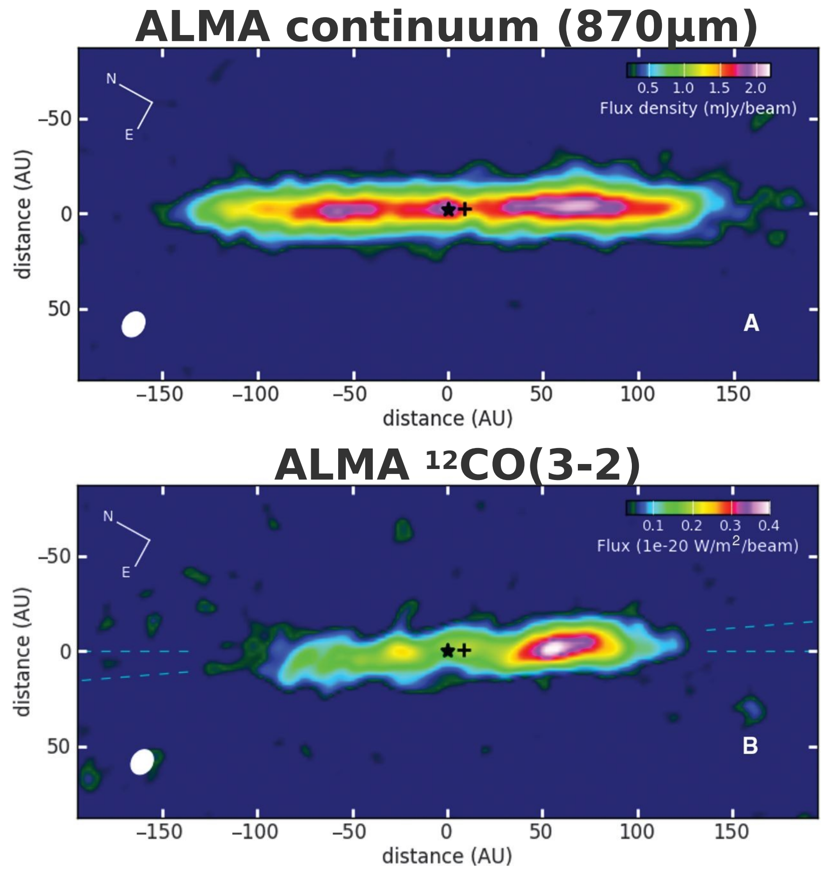
- CO could be a good tracer of gas both in the primordial and secondary scenarios.
- Molecules are photodissociated by UV photons from the central star and interstellar radiation field. Without any shielding the lifetime of CO is ~120 yrs (just ISRF, no stellar photons, Visser et al. 2009).
  - Shielding by dust is negligible (tenuous disks).
  - In secondary scenario: no H_2, only CO self-shielding.
  - In primordial scenario: shielding by H_2 & CO self-shielding. Lifetime could be significantly longer.
- Secondary gas disks: low number of collisional partners – non-LTE situation - low excitation temperature (T_{ex})
- Low level rotational transitions of CO at (sub)millimeter wavelengths are ideal. Emission from a rotating disk: double peaked (Keplerian) profile (immediate evidence for circumstellar origin)

CO surveys of debris disks

- Surveys so far:
  - **With single dish telescopes**: Zuckerman et al. (1995, IRAM), Dent et al. (2005, JCMT), Hales et al. (2014, APEX+ASTE), Moór et al. (2011, 2015, APEX+IRAM).
    - Mostly young debris disks in the southern hemisphere were targeted. In total ~70 objects, 3 detections: **49 Cet** (Zuckerman et al. 1995, Dent et al. 2005); **HD 21997** (Moór et al. 2011); **HD 131835** (Moór et al. 2015)
  - **With ALMA:**
    - Survey of Sco-Cen association (PI: J. Carpenter, Lieman-Sifry et al. submitted) - 23 prominent debris disks, 2 new detections: **HIP 76310**, and **HIP 84881** + confirmation of HD 131835.
    - Survey in nearby young moving groups (PI: D. Rodriguez) – 10 disks, no detections.
    - Individual objects: CO detection in **β Pic** (Dent et al. 2014), Fomalhaut (Matrà et al. 2015), HD 107146 (Ricci et al. 2015) - no gas detections.

Gas in β Pic

- A6V type star, eponymous member of the β Pic moving group (~23 Myr old).
- Edge on disk, UV/optical absorption lines: comprehensive gas inventory (e.g. Roberge et al 2000). No H_2 abs. was detected (Lecavelier des Etangs et al., 2001).
- ALMA continuum map: large grains (and planetesimals) are located between 50 and 130 AU. Asymmetric distribution.
- ^{12}CO (3-2) map: rotating gas, with similar spatial distribution to dust (including the clump). Total CO mass: 2.8×10^{-5} M_{earth} (LTE). Optically thin gas with T_{ex} ~ 20K.
- Secondary gas. CO must be continuously replenished from icy planetesimals (rate ~10^{18} kg/yr, 800 Hale-Bopp/yr).

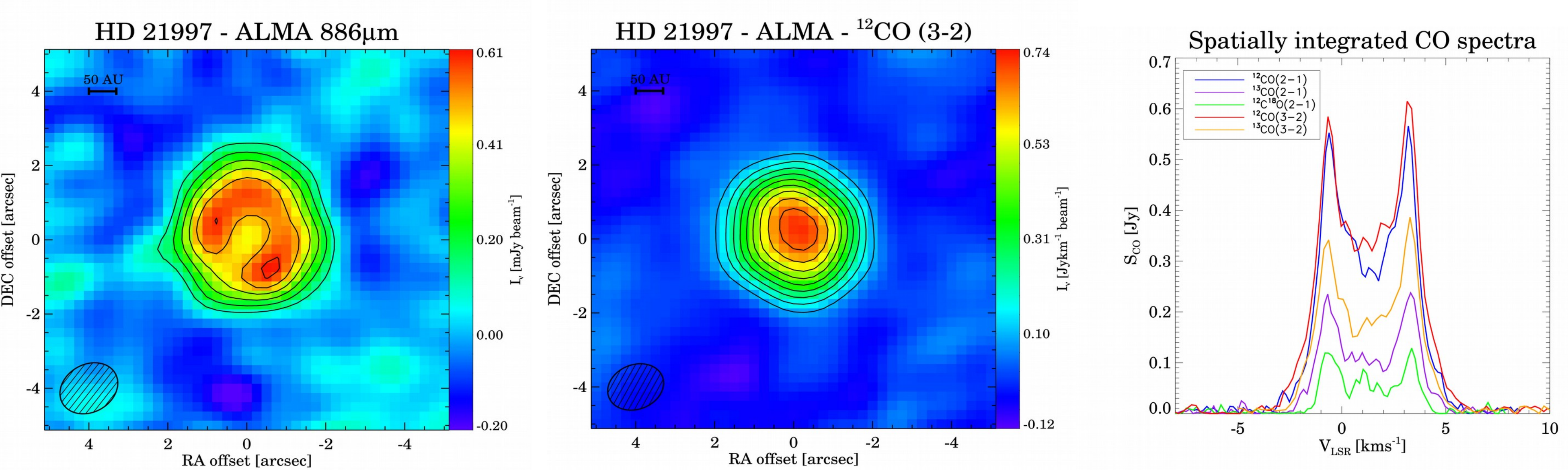


Dent et al. 2014

Further details, new results: presentation of L. Matrà

HD 21997: the first hybrid disk

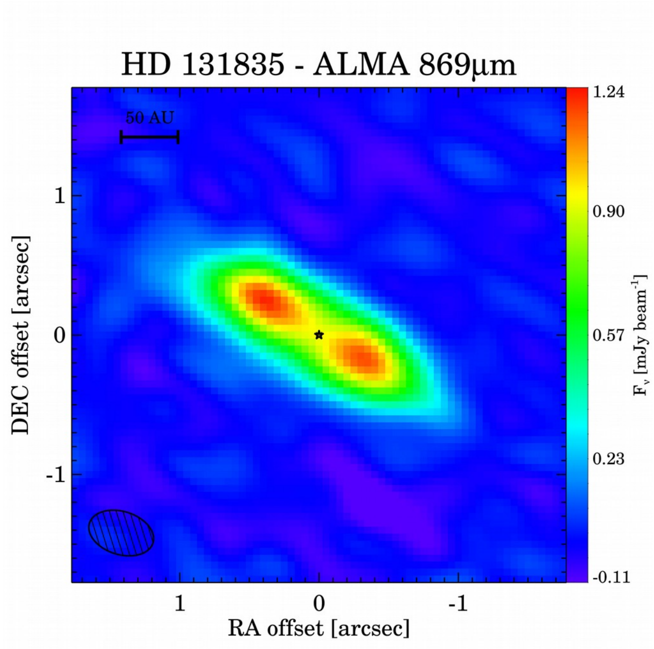
- A3V-type star, member of the Columba association (~30 Myr old).
- ALMA continuum and line observations. All CO lines were detected. No asymmetries. $^{12}CO+^{13}CO$ lines are optically thick. Total CO mass (based on $C^{18}O$): ~0.06 M_{earth}. Low gas temperature: 6-9K (T_{dust} ~ 60K).
- Gas and dust are not co-located, there is a dust-free inner gas disk (within ~55AU).
- Secondary scenario is unlikely: gas production rate needs to be too high (>6000 Hale-Bopp/yr), no co-location. Primordial (leftover) gas scenario is more probable. Total gas mass (with $CO/H_2=10^{-4}$): 30-60 M_{earth}. Hybrid disk: primordial gas with secondary dust grains?

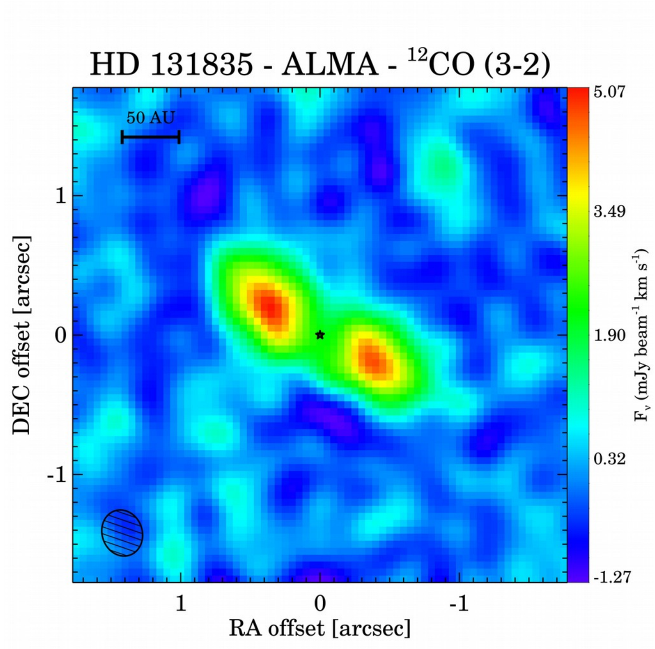


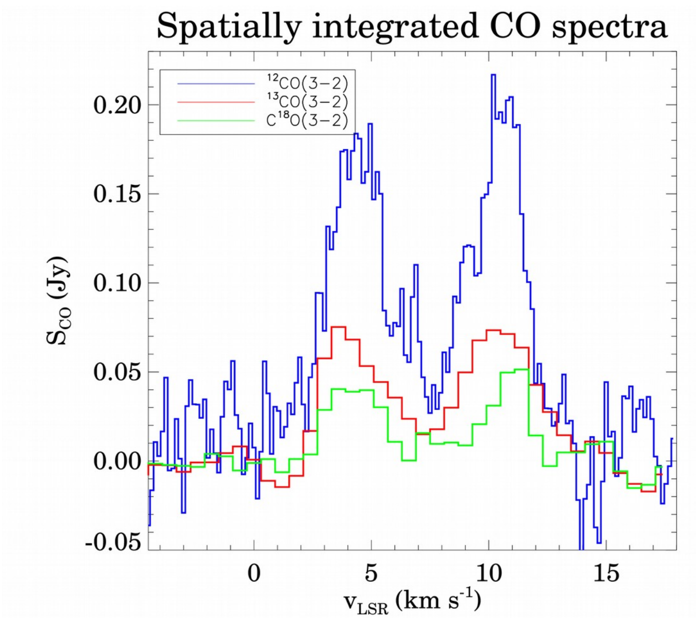
Moór et al. 2013 and Kóspál et al. 2013

HD 131835 (HIP 73145)

- A5-type star, member of the Upper Centaurus Lupus assoc. (~16 Myr old).
- ALMA observations. All CO lines were detected. No asymmetries. ^{12}CO+^{13}CO lines are optically thick. Total CO mass (based on $C^{18}O$): ~0.06 M_{earth}. Low gas temperature: ~10K (T_{dust} ~ 70K).
- Gas and dust are roughly co-located (40-110 AU).
- Primordial gas scenario is more probable.



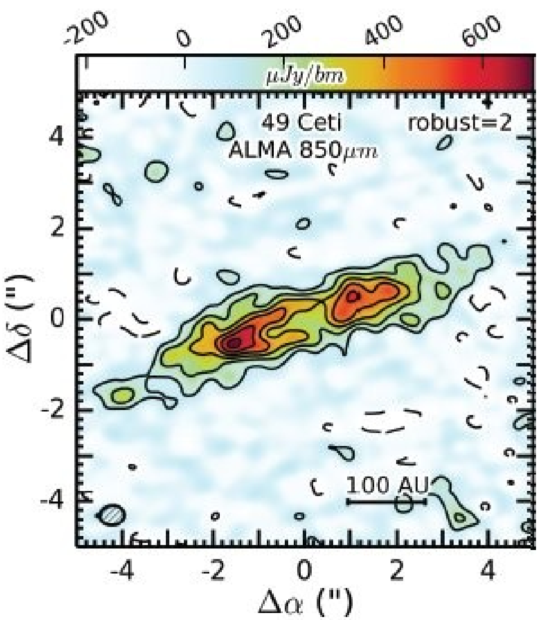


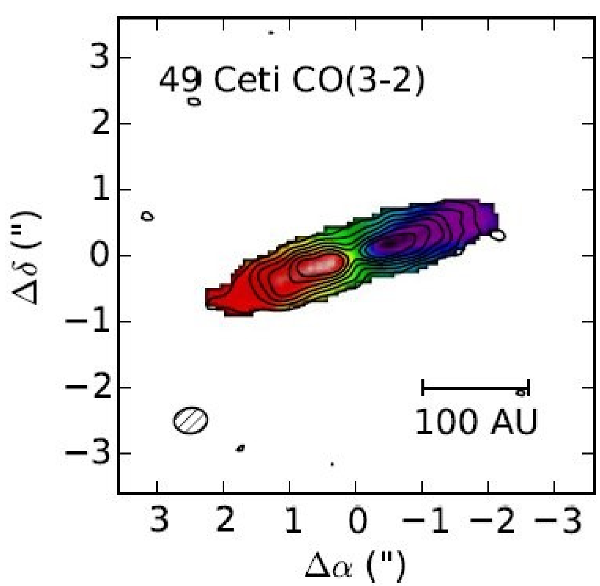


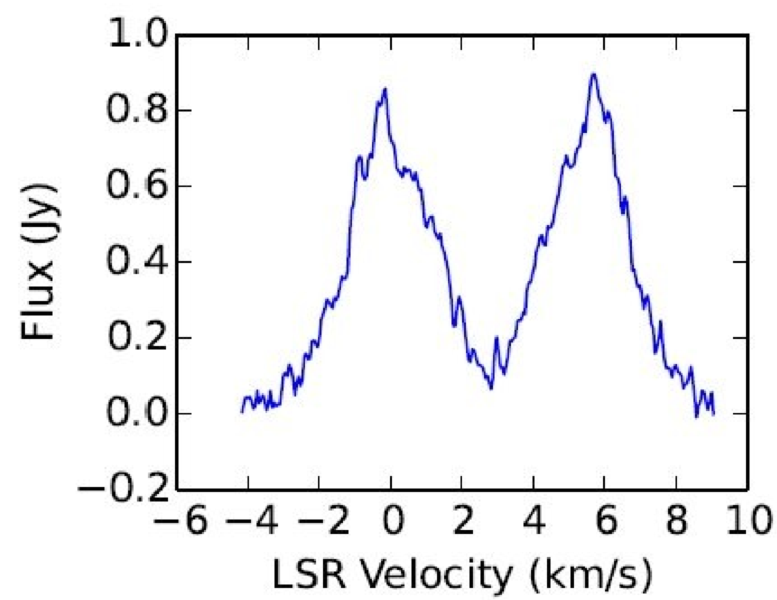
Moór et al. in prep.

49 Cet

- A1V-type star, belongs to the Argus moving group (~40Myr).
- First CO detection in a debris disk (Zuckerman et al. 1995).
- Large grains are distributed between 60 and 300 AU.
- Bulk of the CO mass is co-located with dust.
- None of the dust and gas distribution show significant asymmetries.
- Origin of gas: not clarified yet.



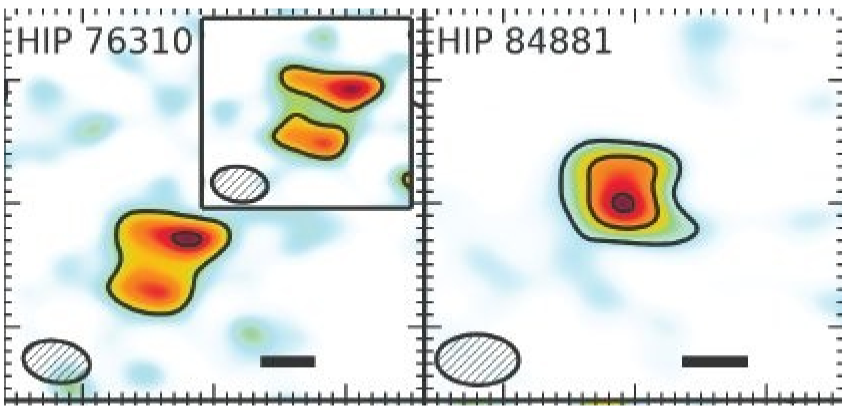


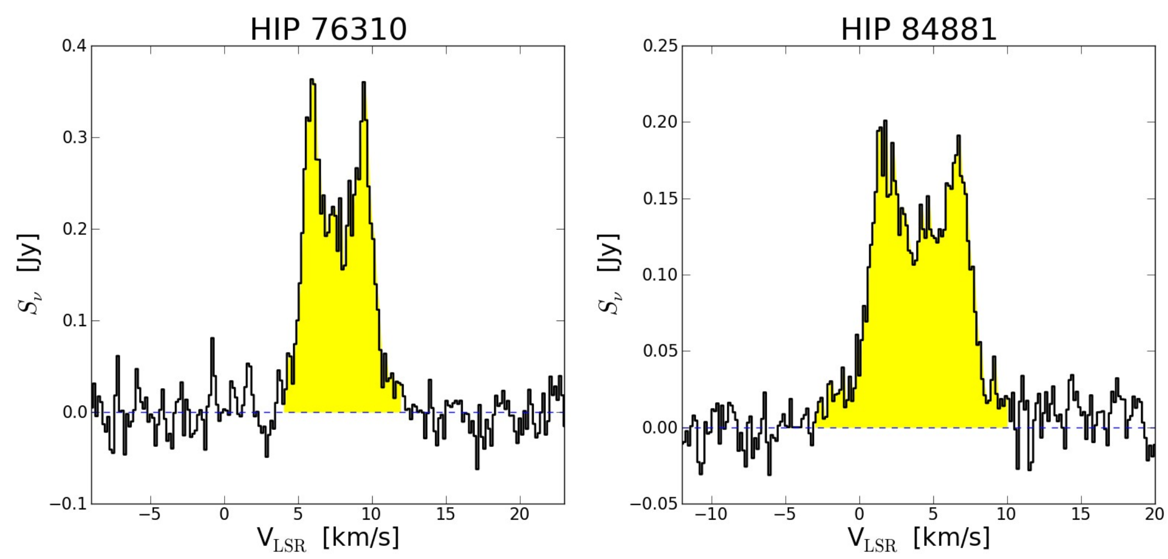


Hughes et al. in prep.

HIP 76310 and HIP 84881

- HIP 76310: A0V type stars in the Upper Sco association (~11Myr old).
- HIP 84881: A0V type stars in the Upper Centaurus Lupus association (~16Myr old).
- ALMA Band6 continuum and ^{12}CO (2-1) observations (part of a larger survey in Sco-Cen association, Lieman-Sifry et al. submitted).
- Extended dust disks.
- Origin of gas is unclear.





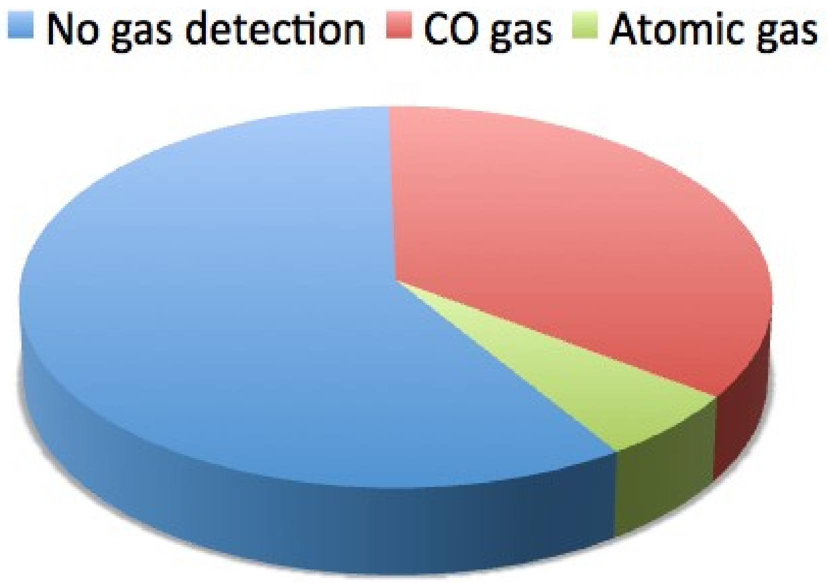
Continuum maps and ^{12}CO (2-1) spectra of HIP 76310 and HIP 84881 with ALMA (Lieman-Sifry et al.submitted)

Main properties of CO bearing debris disks

ID	SpT	Lum. (L_{SUN})	Dist. (pc)	Age (Myr)/Group	L_{IR} / L_{bol}	$T_{dust,cold}$ (K)
49 Cet	A1V	16.4	59	40 / Argus	$1.1x10^{-3}$	56
HD 21997	A3V	11.2	72	30 / Columba	$5.7x10^{-4}$	61
β Pic	A6V	8.7	19	23 / BPMG	$2.6x10^{-3}$	85
HD 131835	A3V	9.2	123	16 / UCL	$3.1x10^{-3}$	71
HIP 76310	A0V	23.1	150	11 / US	$1.5x10^{-3}$	75
HIP 84881	A0V	15.0	118	16 / UCL	$5.5x10^{-3}$	125

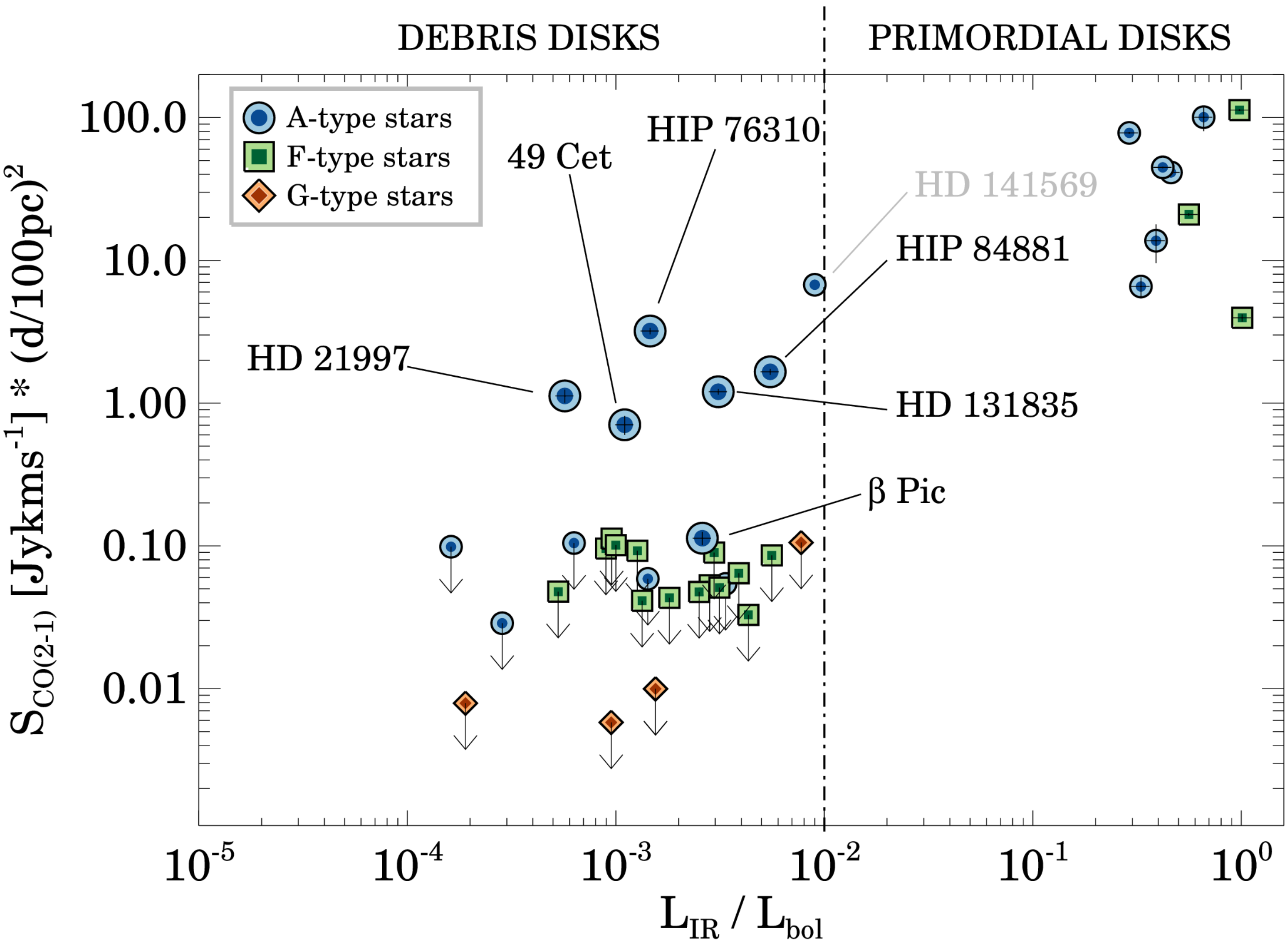
How common?

- Six detections: massive debris disks with L_{IR} / L_{bol} > $5x10^{-4}$, having cold dust component (<130 K), encircle 10-40 Myr A-type stars (all of them are single).
- Within 150 pc we know 17 debris disks having similar properties, all 17 have been searched for CO gas already (9 with ALMA) there are 6 detections, 35% (lower limit). By considering atomic gas line observations the detection rate within this sample is even higher: 7/17.

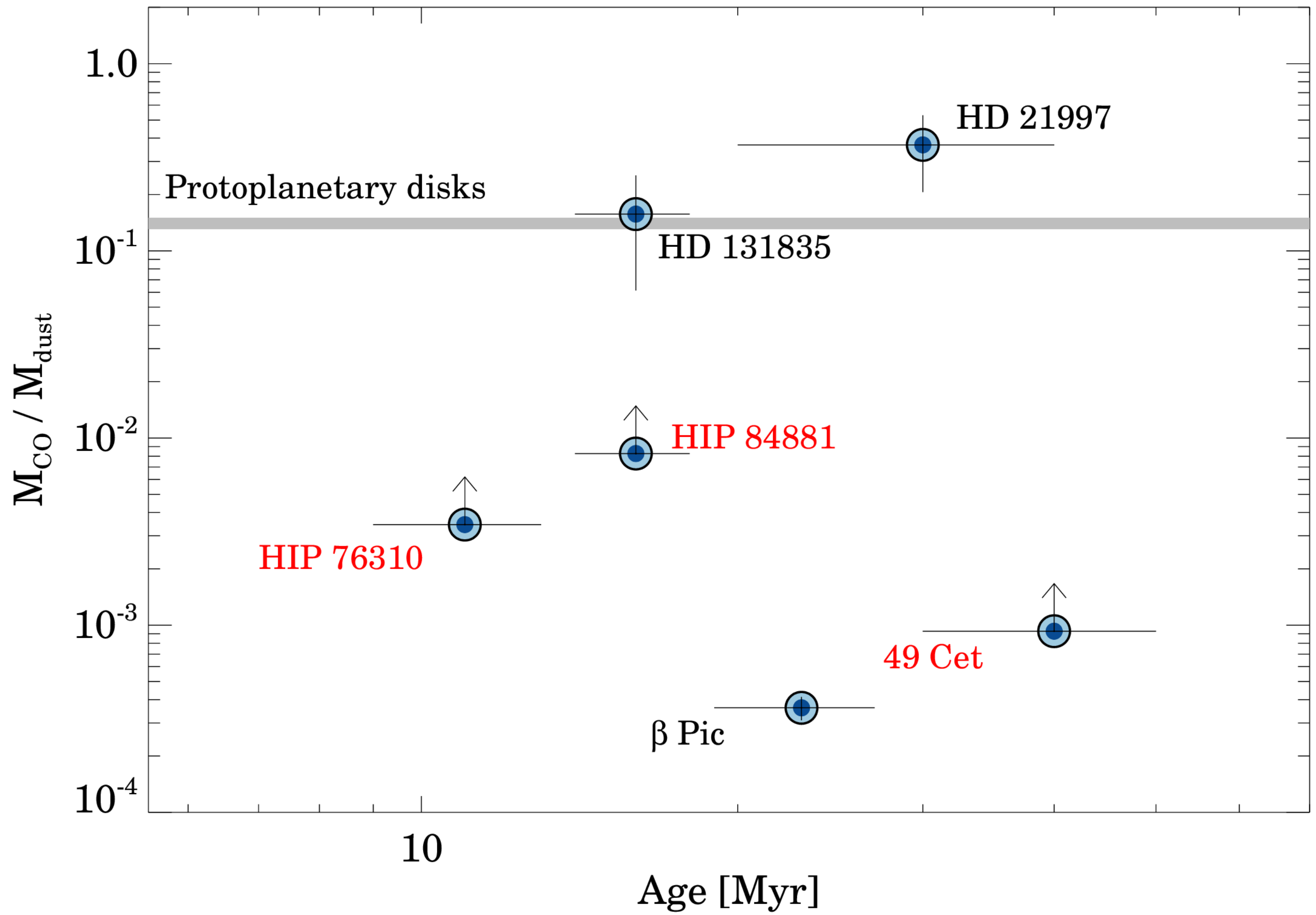


- Sco-Cen survey results a detection rate of 3/7 for B9-A9 stars while it was 0/16 for F0-G1-type systems (with similar fractional luminosity).
- **Gas in massive debris disks around young A-type stars is common. In F-G-stars: one gas detection at HD 181327 (see presentation of S. Marino).**
- In the relevant young moving groups (US, UCL, BPMG, Columba, Argus) the most massive debris disk around A-type star harbors gas.

Integrated $^{12}CO(2\text{-}1)$ fluxes vs. fractional luminosities based on ALMA



CO-to-dust mass ratios vs. age for gaseous debris disks

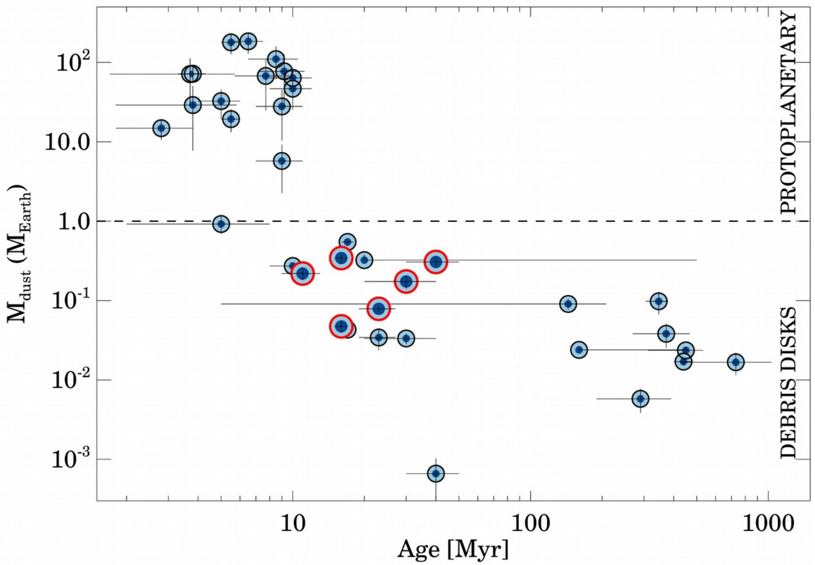


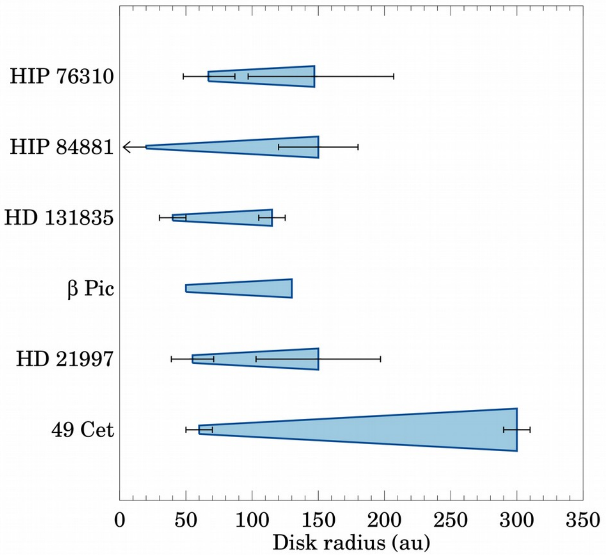
General gas properties

- Gas temperature: cold gas, T_{gas} is lower than the characteristic dust temperature.
- Apart from the case of β Pic, no significant asymmetries are observed in distribution of dust and gas.
- Two systems - HD 21997, HD 131835 - may harbor leftover primordial gas, while β Pic is with secondary gas. In the remaining three systems the origin of gas is unclear yet.
- Integrated CO line flux of HD 21997 and HD 131835 is just below that of faintest protoplanetary disks, while β Pic is fainter by an order of magnitude.
- 49 Cet, HIP 76310 and HIP 84881 exhibit ^{12}CO emission of comparable level than that of the two known hybrid disks.
- ^{12}CO emission could be optically thick in most known gaseous systems. Observation of CO isotopologue is needed to better estimate the CO mass and the CO-to-dust mass ratio.
- In M_{CO}/M_{dust} the difference between β Pic and the two hybrid disks is even more pronounced.

Dust properties

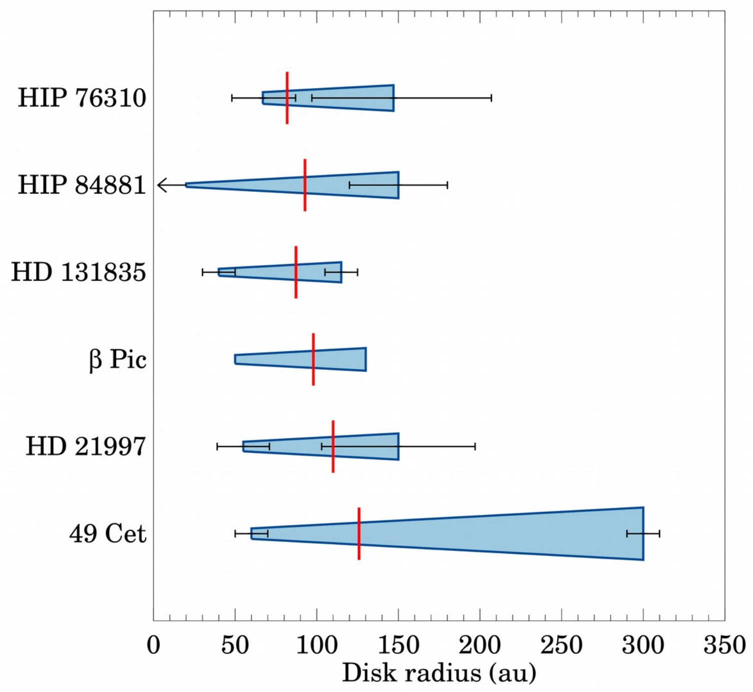
- CO rich debris disks are similar – in terms of dust properties – to „normal“ debris systems: $L_{IR}/L_{bol} < 10^{-2}$, $M_{dust} < 1\ M_{earth}$, no PAH emission, no extreme submm. slope.
- Do they exhibit some special property within debris disks?
  - They are the most massive among debris disks.
  - All have very broad disks ($\Delta R / R \geqq 0.7$) in large grain distribution (i.e. planetesimals). In Sco-Cen (Lieman-Sifry et al.): CO-rich disks are on average spatially more extended than gas-poor systems.





Stirring of the disk

- For destructive collisions: planetesimals' motion have to be dynamically stirred.
- Self-stirring: dynamical excitation by Pluto-sized bodies embedded in the belt (Kenyon & Bromley 2008). The formation timescale of such large perturbers depends on the initial disks mass. Unfeasible in these disks, would require too large initial disk masses.
- Planetary stirring: secular perturbation by a giant planet. Massive planets (2-3 M_{JUP}) on eccentric orbit (*e* ~ 0.2-0.4) located close to the inner edge of the disks can excite planetesimals' motion even at the outer edge of the disks.



- Alternative explanation: dust particles in the outer regions have also primordial origin.

Open questions

- Disks with leftover gas:
  - What is the fraction of hybrid disks among gaseous debris disks?
  - Is this phenomenon limited to intermediate mass stars? If, yes, why?
  - How long primordial gas can survive?
  - Are they really the end state of transitional disk evolution? Does their gas component (e.g. in composition) resemble that of transitional disks?
  - How the presence of long lived gas affect on formation of (giant) planets? (current results: apart from β Pic no planets were found in these systems)
- Disks with secondary gas:
  - What is the typical M_{CO}, M_{CO}/M_{dust} in these systems? β Pic is a young secondary gas disk with an enhanced gas production or is it typical?
  - How do the different mechanisms (collisions, photodesorption) contribute to the gas production?
  - Gas composition?
  - Long term evolution of gas content?

Summary

- There is a growing sample of circumstellar disks that exhibit debris disk like dust properties but harbor detectable amount of gas as well. Six (now seven considering the discovery of gas in HD 181327) of them show evidence for CO gas.
- Molecular gas in massive debris disks around young A-type stars is common. It is less prevalent in disks around young F-G-type stars.
- Common disk properties: broad disks with massive dust component (in terms of debris disks), low gas excitation temperature, apart from the case of β Pic no significant asymmetries are observed in spatial distribution of large grains and gas.
- Origin: at least two gaseous debris disks may harbor leftover primordial gas, i.e. likely being hybrid disks (but we cannot completely rule out that a fraction of dust particles are indeed primordial as well). In β Pic the gas is also secondary.
- Hybrid disks: do not fit into the current paradigm, may affect disk evolution theory. Do they represent the final phase of transition disk evolution?